UPDATES, STATUS AND EXPERIMENTS OF CLEAR, THE CERN LINEAR ELECTRON ACCELERATOR FOR RESEARCH

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Abstract

Operating since 2017, the CERN Linear Electron Accelerator for Research (CLEAR) is a user facility providing electron beams for a large and varied range of experiments. The electron beam is produced from a Cs_2Te photocathode and is accelerated between 60 MeV and 220 MeV in a 20 m long linear accelerator (LINAC). The accelerated beam is then transported to an experimental beamline, in which experiments such as irradiations on electronics, irradiations for medical applications, plasma-lens experiments and beam-diagnostics development are performed. In this paper, the status, the upgrades of the beamline and the recent and future experiments are presented.

INTRODUCTION

The CLEAR facility offers to its users an electron beam with a large range of parameters [1–4]. They are shown in Table 1 and in Fig. 1. A diagram of the beamline is shown in Fig. 2. Two in-air test areas area available. The first is mostly used for VESPER (Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments) while the second In-Air Test Area is for more general use. In practice, both areas can be used for medical applications studies like Very High Energy Electron (VHEE) radiotherapy, the sterilisation of personal protective equipment research studies [5, 6] and irradiations of electronics [7–10], including components of ESA's JUpiter ICy moons Explorer (JUICE). These and other in-vacuum test areas are also used for experiments with in-beam instrumentation [11] and novel accelerator technology studies like plasma lenses [12–14].

CLEAR is a fully independent installation and doesn't require any other accelerators from the CERN Accelerator Complex to run. Thus, the machine can run during LHC's long shutdowns and upgrades. The beam schedule is very flexible: a usual beam access is scheduled on Monday mornings to install the experiment of the week and the machine can run from 8 to 12 hours per day, 5 days a week, depending on the needs of the users. The machine ran for 38 weeks in 2019, 34 and 35 weeks during the 2020 and 2021 COVID-19 crisis. In September 2020 the CERN Council approved the CERN Medium Term Plan which extends CLEAR operation until 2025.

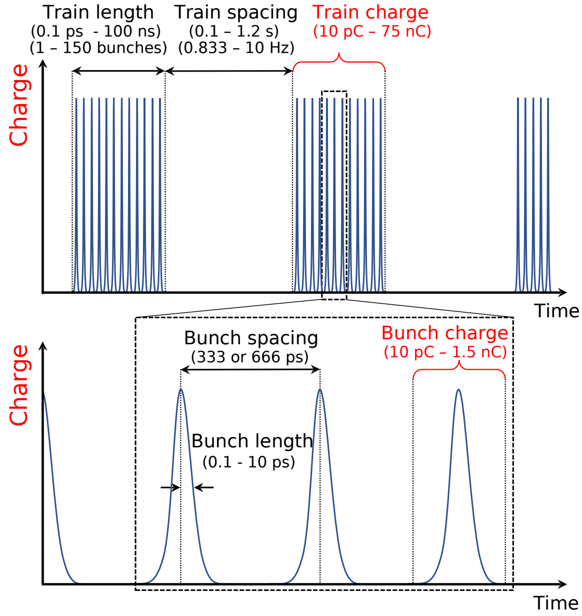

Figure 1: CLEAR beam time structure and charge parameters at the end of the beam line in 2022.

Table 1: Updated List of CLEAR Beam Parameters

Parameter	Value
Beam Energy	60 – 220 MeV
Beam Energy Spread	$< 0.2\%$ rms (< 1 MeV FWHM)
Bunch length rms	0.1 – 10 ps
Bunch frequency	1.5 or 3.0 GHz
Bunch charge	0.005 – 1.5 nC
Norm. emittance	1 – 20 μm
Bunches per pulse	$1- \sim 150$
Max. pulse charge	75 nC
Repetition rate	0.8333 – 10 Hz

OPERATION AND PERFORMANCE

During the 2021/2022 winter shutdown several modifications were done to the CLEAR beamline: the CLIC Cavity BPMs and the CLIC structure were removed from the beam line for repairs and diagnostics studies. This leads to a larger beam pipe aperture at these locations and results in a better beam transport at the end of the line.

A new quadrupole (QDD0920) was installed on the In-Air test stand, 1400 mm downstream of the final doublet. The alignment of this last quadrupole has been verified and corrected by the survey group. This quadrupole is used

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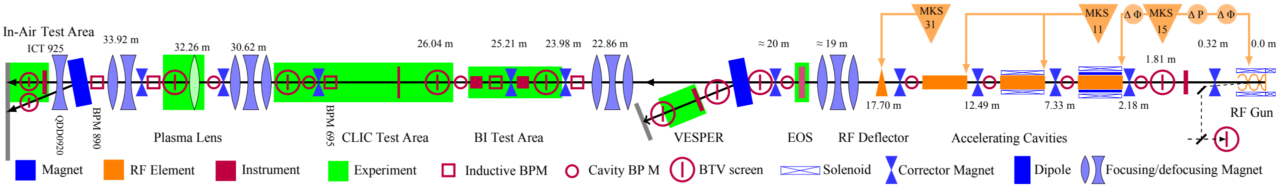


Figure 2: CLEAR beam line in 2022. Notice that the electron beam travels from right to left [2].

for Very High Energy Electron strong focusing studies in a water phantom. These aim to obtain a transverse waist, corresponding to a peak in the dose delivered, at a specific depth in water. This configuration would be used for future potential cancer treatment using electrons. The human body is represented by the water phantom and the waist would be at the tumor cells. This would concentrate the dose on the tumorous cells and spare the surrounding healthy tissues.

The CLEAR photocathode has been renewed. A thin layer of Cs_2Te was deposited by evaporation on the cathode surface. A bunch charge of 1.5 nC is now easily achievable.

The vacuum system was updated and consolidated, offering higher reliability and better vacuum in several beam pipe locations.

Two optical fibres were installed all along the machine next to the beam pipe in order to measure the beam losses and will be used for operation in the future.

The CLEAR on-line optics model has been updated, allowing the operators to immediately estimate the impact of beam optics changes. This has been particularly useful to set-up transverse beam waists in water or in air at the end of the beam line, as described above.

C-ROBOT

In order to increase the range of experiments done in CLEAR, the CLEAR team designed, developed and built a robotic system called CLEAR-Robot (C-Robot). It was designed to easily irradiate samples for medical applications. The robot is made of 3 linear stages for X,Y and Z axis, 6 limit switches (2 for each axis), a 3D printed grabber, a mounted-camera system with a moving filter and two tanks (one storage tank and one tank in the electron beam). A rendered picture of the system is shown in Fig. 3. The C-Robot is fully remotely controlled from the CERN Technical Network thanks to Arduinos and to a graphical user interface as shown in Fig. 4.

There are two separate areas on the C-Robot, the storage area and the beam area. In the storage area, a laser-cut PMMA plate and PMMA water tank are installed and can welcome 32 different 3D-printed holders. Each holder can be adapted for different experiments. Two dosimetric films can be installed on each holder, one before and one after the sample that needs to be irradiated. The transverse and longitudinal positions of the holder in the beam area can be chosen with a 50 µm accuracy.

In order to measure the beam size and position where the samples will be irradiated, a dedicated holder with a YAG screen attached can be inserted in the beam area. The screen is angled by 45° compared to the electron beam and thanks to camera mounted on the C-Robot, the beam position and the beam size of the electron pulses can be measured directly at any transverse and longitudinal positions in the beam area.

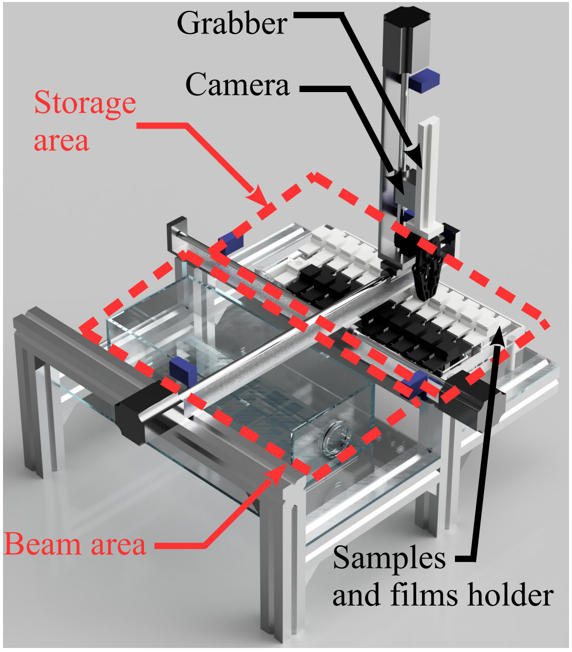
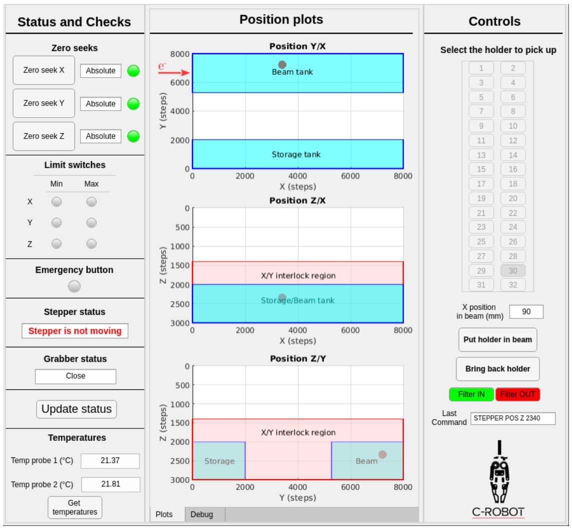


Figure 3: Rendered image of the C-Robot.



Stepper status: Stepper is not moving
Grabber status: Close
Temp probe 1 (°C) 21.37
Temp probe 2 (°C) 21.81
X position in beam (mm) 90
Last Command STEPPER POS Z 2340

Figure 4: Snapshot of the C-Robot Graphical User Interface.

The C-Robot is fully open-source. Pictures, drawings, 3D renders and codes can be found on the C-Robot website [15] and on the C-Robot Gitlab Repository [16].

EXPERIMENTAL PROGRAM

The CLEAR experimental program has expanded with time and the following experiments were or will be performed in the accelerator:

Plasma Lens

Active plasma lenses is a technology that enables strongly focusing magnetic lenses for charged particle beams. Unlike classical magnetic quadrupoles, they focus the beam in both transverse planes simultaneously, and are very compact. A single lens would then replace several magnets to control the beam size, and may have important applications for future linear colliders and particle sources. The more recent results obtained with the CLEAR Plasma Lens are described in [17]. With argon in a 500 µm diameter capillary the fields are still linear with a focusing gradient of 3.6 kT/m, which is an order of magnitude higher than the gradients of quadrupole magnets. The current pulses, up to 800 A, that generate the magnetic field are provided by compact Marx banks, and are highly repeatable. The demonstrated operation establish active plasma lenses as an ideal device for pulsed particle beam applications requiring very high focusing gradients that are uniform throughout the lens aperture.

Beam Diagnostics Development

Numerous beam diagnostic tests were also carried out in CLEAR [11] including High frequency Beam Position Monitor (BPM) for the AWAKE experiment, LHC dielectric Cherenkov Diffraction Radiation (ChDR) pick-ups, charge calibration of the AWAKE spectrometer screen, micro Beam Profile Monitors, CLIC Cavity-BPMs, Bunch Length monitor based on Cherenkov diffraction, Wall Current Monitor from Bergoz Instrumentation, etc.

Radiation to Electronics

Since its creation, CLEAR was often used for electronic components irradiation (R2E). The goal is to to verify their functionality in radiation environments. CERN and the European Space Agency (ESA) are using CLEAR electron beams to test their devices in particular in VESPER. VESPER's high energy electron beamline was used to simulate the conditions within Jupiter's massive magnetic field, which has a million times greater volume than Earth's own magnetosphere, trapping highly energetic charged particles to form intense radiation belts. Electronics from ESA's JUpiter ICy moons Explorer (JUICE) were thus tested in the high-radiation environment at CLEAR [8].

Irradiations for Medical Applications

Several medical application experiments were done in CLEAR in 2021/2022, in particular in collaboration with the Centre Hospitalier Universitaire Vaudois (CHUV). They addressed the use of Very High Energy Electrons (VHEE) beams for cancer radiotherapy. VHEE beams are a promising candidate for treating deep-seated tumours due to their highly penetrating dose distributions and lack of sensitivity to inhomogeneities. The main topics were: a) Dosimetry for (VHEE), in particular at Ultra High Dose Rates (UHDR) (testing detectors, use of standard e-beam diagnostics for dose rate evaluation in real time). Different types of dosimetry for VHEE were tested: Gafchromic films, Radio-Photo-Luminescence Dosimeter (RPL), real-time detectors like diamond or silicon, etc. b) studies on Chemistry (e.g., Oxygen Peroxide production in water) and Biological effects (e.g., on Plasmids and Zebra-Fish Eggs) at very high dose rates, with the goal to study the FLASH effect, the biological response due to a very fast dose delivery which has been shown to partially spare healthy tissues.

VHEE Strong Focusing

The entrance dose due to VHEE beams could be reduced by focusing using quadrupole magnets. It is also possible to use multiple focused beams to treat a target region using VHEE. The VHEE Strong Focusing experiment aims to show highly penetrating, focused VHEE at depths >10 cm into a water phantom, and show the possibility to treat a target region using three focused VHEE beams delivered in a weighted way to produce a spread out dose peak [18].

VHEE Scatterers

A VHEE treatment beam would require several key characteristics to be met after initial acceleration. The beam would be required to have a uniform transverse profile at the patient. These steps could be achieved entirely through beam optics, however, the solution would likely be susceptible to initial beam distribution, misalignment and jitter. Furthermore, in the case of a rotating gantry, the cost of rotating many large, heavy quadrupoles would be high. Another solution is to achieve the magnification with a flat scattering foil, and the flattening with a foil with a more complex shape. Such scatterers were and will be tested in CLEAR.

CONCLUSION

CLEAR just entered its sixth year of operation and the experimental parameter range available to users is larger than ever before, which makes CLEAR, among other things, a unique VHEE and UHDR test facility. CLEAR can now offer a higher bunch and train charge, a more stable beam, shorter bunches and longer bunch trains. New tools are also available, in particular the C-Robot which offers a really versatile and adaptive instrument for irradiations, beam position and size measurements, insertion of scatterers or samples, etc. In the future, CLEAR plans to increase its parameter range with a second beamline, a second source, and potentially installing the X-Band Klystron in order to test a high-gradient accelerating structure.

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